Improving Air-Sea Coupling Parameterizations
in High-Wind Regimes

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LONG-TERM GOAL

The long-term goal of this PI team is to understand the physical processes of the air-sea interaction and coupling of the atmosphere-ocean system in high-wind maritime regimes, with a particular emphasis on hurricanes, and to determine the changes that must be made to the coupled atmosphere-wave-ocean models in order to simulate the coupled boundary layers under extreme wind conditions.

OBJECTIVES

The main objectives of this study are 1) to develop improved subgrid-scale (SGS) parameterizations for modeling the atmosphere boundary layer (ABL) structure in high-wind regimes using a large-eddy simulation (LES) approach and explore the effects of sea spray on the ABL through LES experiments, 2) to improve drag coefficient calculations for high-wind conditions by parameterizing "spectral tails" (wavelength < 10 m) unresolved by the current wave models, 3) to test the sensitivity of mixing schemes in the ocean mixed layer (OML) and examine the effects of the ocean waves on the OML dynamics, and 4) to develop atmosphere-wave and atmosphere-ocean generic couplers to allow the flexibility of testing various physical parameterizations and different models in the coupled system.

APPROACH

Our current focus is to study the nature of coupled atmosphere-ocean boundary layers and heat and momentum exchange at the air-sea interface in hurricanes. The extreme high winds, intense rainfall, large ocean surface waves, and copious sea spray push the surface-exchange parameters for temperature, water vapor and momentum to untested new regimes. We will develop improved parameterizations of subgrid-scale processes, air-sea exchange coefficients, and surface fluxes in coupled atmosphere-wave-ocean models with high-resolution (~1-2 km grid spacing) that can resolve the hurricane eyewall structure. The RSMAS/UM PI team is focusing on the effects of ocean wave "spectral tails" on drag coefficient, wind-wave coupling, and ocean mixed layer parameterizations. The PSU PI team develops improved parameterizations of subgrid-scale processes in ABL. The methodology is to use a Large-Eddy Simulation (LES) initialized for hurricane-like conditions,

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including very high winds, sea spray, and the effects of waves at the lower boundary. These parameterizations would then be installed and tested in the coupled atmosphere-wave-ocean models like the coupled modeling system at RSMAS/UM and the U. S. Navy's COAMPS. We will work closely with other CBLAST PI teams working on obtaining new observations of hurricanes to evaluate our model results.

WORK COMPLETED

RSMAS/UM team:

During the second year of this five-year CBLAST project, we have established several key steps toward developing a set of new coupling parameterizations for a fully coupled atmosphere-wave-ocean modeling system for hurricane research and prediction. The components of the coupled systems are the PSU/NCAR MM5, WAVEWATCH III (WW3), and the University of Miami HYCOM. Progresses are made in the four main areas. First, in addition to the model simulation of Hurricane Floyd (1999), we have completed a 5-day wave model simulation of Hurricane Bonnie (1998) forced by the high-resolution surface winds from MM5. Using a vortex-following, four-level nested grids MM5, we are able to conduct a 5-day long simulation to capture the evolution and the landfall of Hurricane Bonnie at 1.67 km grid resolution on the inner-most domain (Rogers et al. 2002). The NECP global analysis fields and the high-resolution (~9 km) AVHRR Pathfinder analysis (Chen, et al., 2001) are used to initialize MM5 and provide continuous lateral and lower boundary conditions. Second, we have evaluated/validated model simulated surface wave spectra with observations both over the open ocean and at the landfall (Walsh et al. 2001). We have also conducted a number of sensitivity simulations using various spatial and spectral resolutions in the wave model to examine the impact of the resolution on model simulated surface wave properties. Third, we developed an atmosphere-wave coupler and conducted several coupled MM5-WAVEWATCH simulations with various coupling schemes, including both non-directional and directional stress coupling, with and without the "spectral tails" parameterization. Forth, we have added new vertical mixing submodels to HYCOM, and has validated the performance of the model and the hybrid vertical coordinate adjustment algorithm using all available vertical mixing algorithms.

PSU team:

The PSU PIs and Graduate student Mark Kelly have made progress on three fronts: developing a strategy for including surface wave and spray effects through the lower boundary conditions on the LES; incorporating phase change in the code, including fractional condensation on the subgrid scale; and including the dynamic effects of liquid water (sea spray) in the LES equations. Over the past year, we have incorporated water vapor and liquid water into our pseudospectral LES code. The liquid water, which includes condensate as well as sea spray, induces substantial buoyancy forces in the LES equations of motion. We have found the spray in particular to have significant dynamical effects; through its upward buoyancy flux it has a large stabilizing influence that damps turbulent motion. We have developed a new subgrid model for the LES code specifically for the region adjacent to the surface (Wyngaard et al., 2002). There the standard Smagorinsky model has a number of deficiencies that limit its ability to couple boundary-layer flow to the underlying surface (Wyngaard et al., 1998). These stem from its assumed Newtonian stress-deformation rate relationship, which implies a scalar subgrid-scale eddy diffusivity. Observations (e.g., Wyngaard et al., 1971) show the eddy diffusivity for momentum and advected scalars near the surface is a second-order tensor. Our new model has tensor eddy diffusivities, and also allows local transfer of energy from smaller to larger scales. It is much

better suited to coupling with the disturbed ocean surface, which we shall do through the modulation of vertical air velocity.

RESULTS

Spray affects the hurricane boundary layer in several important ways. The weight of the liquid water increases net air density, while evaporation of spray tends to cool and moisten the air (though there may still be a net flux of energy from the sea to the air due to spray). We hypothesize that the net effects of spray will include suppression of boundary layer turbulence due to increased stability and a resultant reduction in net surface-to-air energy fluxes. Figure 1 shows results after one hour for runs with 80x80x80 grid points [1 km^3 domain, 12.5 m grid spacing, geostrophic wind velocity of 100 m s^{-1}, a surface-spray flux of 5 m s^{-1} g kg^{-1}, a surface heat flux of ~ 300 W m^{-2}, a capping inversion at 600 m, an initial bottom temperature of 298K above a flat surface with roughness length of 0.1m] both without (dotted lines) and with (solid lines) non-evaporative spray. The center plot shows that the buoyancy effects of spray can overcome the rate of buoyant production of turbulent kinetic energy (TKE) due to surface heat flux, resulting in an overall destruction of TKE. The right-most plot shows the ratio of the rates of buoyant destruction and shear production of TKE (flux Richardson number, R_f). Generally, above $R_f \sim 0.25$ (red line in plot) turbulence is unsustainable, and we can see that over some heights this occurs and thus the spray is effectively damping the turbulence. The left-most panel shows the vertical profile of the spray liquid water mixing ratio averaged for the same time interval. The maximum spray values near the surface, about .030 g/g, are well within realistic bounds and may well be low for a storm with such high wind speeds.
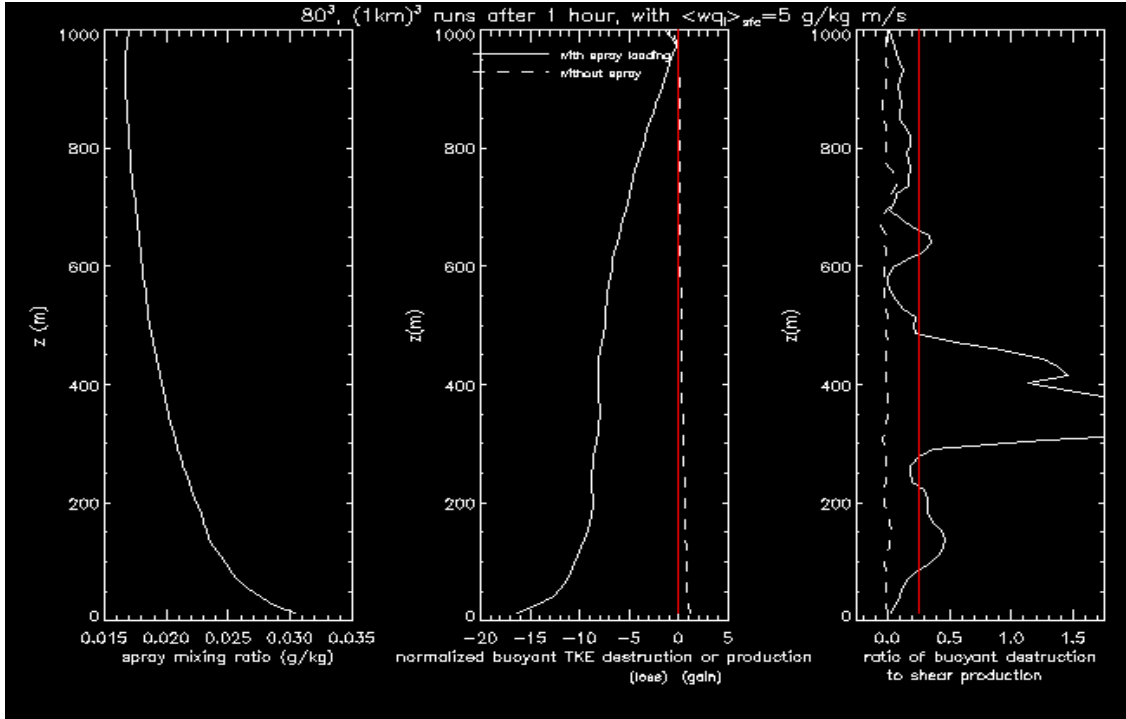
Fig. 1 Results from the LES (described in details in the text).

Our scheme for incorporating evaporative sea-spray into the LES code has several nice features. First, it is consistent with the current Runge-Kutte variable time-step framework, accommodating the high time resolution necessary for the hurricane boundary layer. The evaporative spray scheme is also amenable to both diagnostic and prognostic methods. We will change the phase-change modeling to fully prognostic in a way consistent with interactive dynamic sea surface boundary conditions. Finally, the spray coding allows incorporation of multiple 'species' of spray, to enable treatment of the different evaporation rates, surface fluxes and fallout velocities of various spray droplet sizes.

The high-resolution (~1.6 km grid spacing) MM5 simulations of Hurricane Bonnie (1998) and Hurricane Floyd (1999) show complex patterns of surface fluxes near the inner core of the hurricane as reported previously. The corresponding wave model simulations with the two different wind forcing show a significant difference in both significant wave heights and wave spectra. Model simulated SWH, and wave periods compare well with observations from the NDBC buoy (Fig. 2).
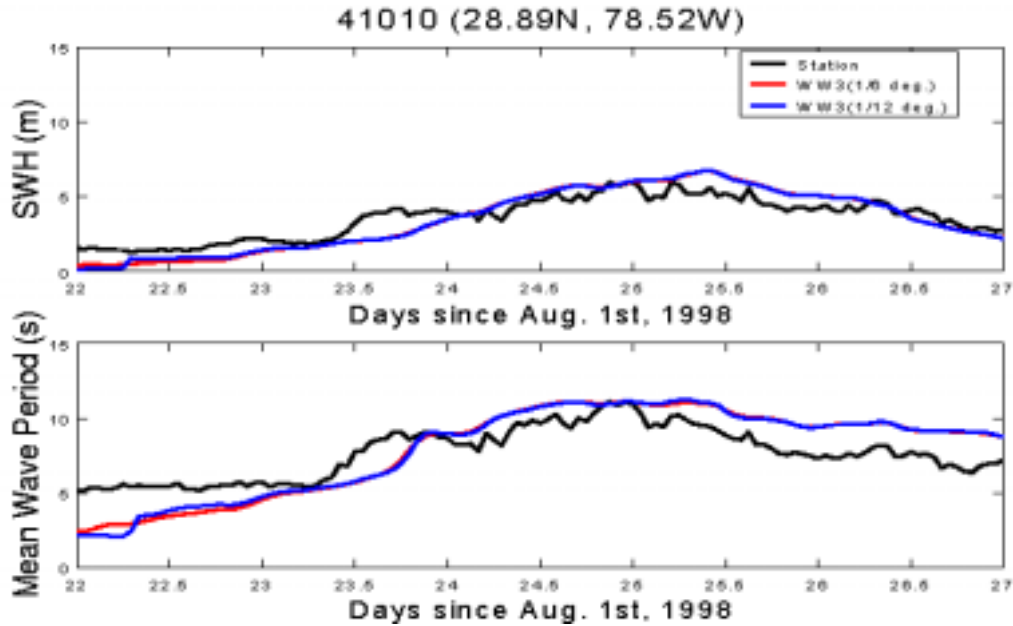
Figure 2. NDBC Observed (black) and WW3 model simulated (red and blue) significant wave height (upper) and mean wave period (lower) in Hurricane Bonnie (1998).

One of the questions is whether the model simulated surface wave property is sensitive to the spatial resolution of WW3. Our simulations indicate that the difference between the 1/6 and 1/12 degree resolutions is very small (Fig. 2).

We have conducted a number of coupled MM5-WW3 simulations to investigate the sensitivity of model simulated hurricane intensity to various wind-wave coupling parameterizations. Fig. 3 shows the simulated minimum sea level pressure (SLP) for Hurricane Floyd (1999) using three different wind-wave couplings 1) roughness length from a simple friction velocity relationship, 2) wave-age dependent roughness length, and 3) directional stress coupling with our spectral-tail parameterization.

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The storm intensity varies by 10-20 hPa with different wind-wave couplings. The directional stress coupling seems to be the closest one to that observed from the best track record.

IMPACT/APPLICATIONS

Over the last a few decades hurricane track forecasts have improved significantly, whereas very little progress made in hurricane intensity forecasts. The lack of the skill in the intensity forecasts can be attributed, in part, to deficiencies in the current operational prediction models: insufficient model resolution, inadequate surface and boundary layer formulations, and lack of full coupling to the ocean. This project will provide improved physical parameterizations for the coupled atmosphere-wave-ocean models at very high spatial resolution. It will make a significant contribution to improve hurricane intensity predictions.
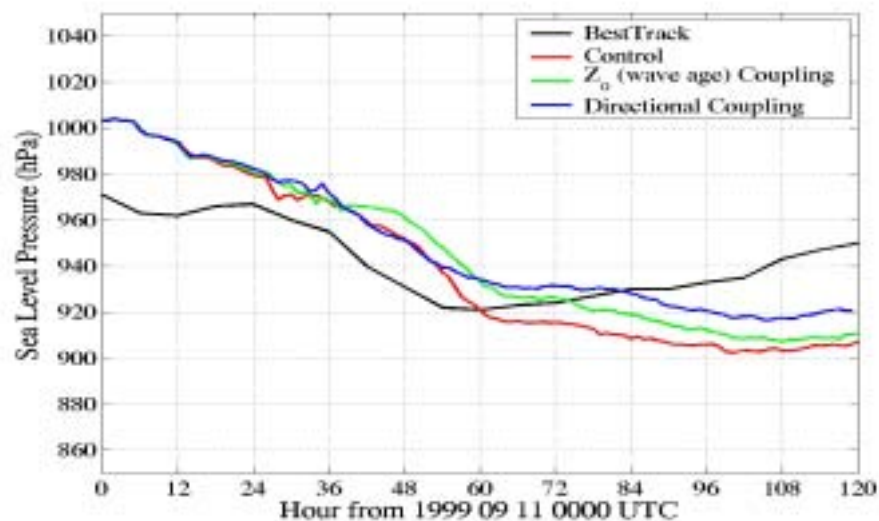
Fig. 3 Coupled MM5-WW3 simulations of storm intensity for Hurricane Floyd (1999) using three different wind-wave coupling parameterizations.

TRANSITIONS

We will assist in the transitioning of the completed parameterizations to operational coupled modeling systems (e.g., COAMPS). These new parameterizations developed at RSMAS/U.Miami and Penn State will be made available for all ONR CBLAST PIs.

RELATED PROJECTS

Related projects include the NSF/NOAA/ONR USWRP on Rainfall of Hurricanes at Landfall (S. Chen), the NASA/JPL QuikSCAT (S. Chen), ONR HYCOM Consortium for Data Assimilative Ocean Modeling (E. Chassignet, G. Halliwell, et al.), and ONR CBLAST-Hurricane (P. Black et al.).

PUBLICATIONS

Chen, S. S., W. Zhao, J. E. Tenerelli, R. H. Evans, and V. Halliwell, 2001: Impact of the AVHRR sea surface temperature on atmospheric forcing in the Japan/East Sea, *Geophys. Res. Lett.,* **28***,* 4539-4542.

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